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Design and Development of a Portable Solar-Powered Water Purification System with Automated Multi-Stage Filtration for Off-Grid Application

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Abstract

Access to clean drinking water is a significant challenge in remote areas, where traditional treatment systems often struggle due to their reliance on electricity and high costs. This study introduces a compact solar-powered water purification system designed for sustainable and portable clean water production. The system features solar photovoltaic panels, a lithium-ion battery, and a multi-stage filtration unit with reverse osmosis and activated carbon filters to remove contaminants, including heavy metals and microorganisms. A simplified automation system with a float switch sensor and manual override helps manage pump operation and prevent overflow. An energy management system ensures a stable power supply despite varying solar conditions. Testing demonstrated significant improvements in water quality, confirming the system's effectiveness. Cost analysis suggests that this prototype is a low-cost, energy-efficient solution for rural areas. In conclusion, the solar-powered water purification system offers a practical approach to improving water access in underserved communities.

1. Introduction

Access to safe and clean drinking water remains a major global challenge, particularly in rural and remote communities. According to the 2023 UN World Water Development Report, approximately half of the world's population relies on contaminated water sources, while more than 2.4 billion people lack adequate sanitation facilities [1]. These conditions contribute significantly to waterborne diseases, poor public health, and reduced quality of life. Although centralised water treatment systems have been widely implemented in urban areas, such infrastructure is often unavailable in remote locations due to high installation costs, maintenance requirements, and dependence on a continuous electrical power supply.

Solar-powered water purification technologies have emerged as a promising alternative for off-grid communities due to their sustainability and environmental friendliness [2], [3], [4]. Various approaches, such as reverse osmosis (RO), ultraviolet (UV) disinfection, activated carbon filtration, and hybrid purification systems, have been explored in recent years. However, many existing solar-powered systems face several limitations, including high capital costs, low water production rates, complex system integration, and inadequate energy management. Additionally, most reported systems lack portability and modularity, making them unsuitable for deployment in remote and emergency scenarios. Furthermore, limited research has been conducted on integrating automation features, such as water-level monitoring, smart pump control, and energy-efficient operation, into compact solar-powered purification systems.

Another critical limitation in current studies is the lack of comprehensive performance evaluation under real operating conditions [5]. Many systems focus only on energy generation or filtration efficiency in isolation, rather than optimising the entire purification process. Moreover, maintenance challenges, operating pressure requirements for reverse osmosis membranes, and energy consumption constraints are often not thoroughly addressed [6]. These gaps highlight the need for a compact, cost-effective, and automated solar-powered water purification system that integrates multi-stage filtration while maintaining operational efficiency and ease of maintenance.

Therefore, this research addresses the need for an affordable and modular solar-powered water purification system suitable for off-grid applications. The proposed system integrates solar photovoltaic (PV) technology with a multi-stage filtration process, including reverse osmosis and activated carbon filtration, and incorporates automation to improve operational reliability and efficiency. The system is designed to be portable, energy-efficient, and capable of providing safe drinking water in remote areas. Accordingly, the objectives of this project are to design and develop a modular solar-powered water purification prototype, implement a multi-stage filtration system, integrate automation features for improved performance, and evaluate the system's operational efficiency, water quality, and overall performance under practical conditions.

2. Solar-Powered Water Purification Systems

Solar energy has long been considered a viable solution for clean water access, particularly through systems that combine solar photovoltaic panels with technologies such as reverse osmosis, UV purification, and activated carbon filtration. These hybrid systems can effectively remove salts, bacteria, viruses, and heavy metals.

2.1 RO Filtration System

Reverse osmosis (RO) is a widely used water purification technique that forces water through a semi-permeable membrane to remove dissolved salts, organic compounds, fluoride, heavy metals such as lead and arsenic, and nitrates [7]. Due to its high contaminant removal efficiency and reliability, RO technology has become a preferred solution for both residential and industrial water treatment applications. The effectiveness of RO systems depends largely on operating pressure, membrane characteristics, and feed water quality.

Typically, RO systems require relatively high operating pressure to overcome osmotic pressure and drive water through the membrane. For brackish water treatment, operating pressures generally range from 5 to 15 bar, while seawater desalination systems may require pressures exceeding 50 bar. These pressure requirements result in considerable energy consumption, particularly in off-grid applications where power availability is limited. Consequently, integrating solar photovoltaic (PV) systems with RO units has attracted significant attention, as solar energy offers a sustainable, renewable power source for remote and rural areas.

Inspired by designs reported in the literature, this project develops a compact, portable solar-powered RO system suitable for off-grid applications. Such systems have demonstrated the capability to meet drinking water standards while improving water quality in rural communities. However, despite their advantages, solar-powered RO systems face several operational challenges, including energy fluctuations due to variable solar irradiance, membrane fouling, and scaling caused by suspended solids and dissolved minerals.

Membrane fouling remains one of the most significant maintenance challenges in RO systems, leading to reduced permeate flow rate, increased pressure requirements, and decreased system efficiency over time. Additionally, certain contaminants such as boron and dissolved gases may not be completely removed by standard RO membranes [8]. Regular maintenance, including membrane cleaning, pre-filtration, and periodic replacement, is therefore necessary to maintain long-term performance and reliability. Furthermore, energy management and proper system sizing are critical to ensure stable operation under varying solar conditions.

Overall, the adaptability of reverse osmosis technology, combined with renewable solar energy, makes it a promising solution for providing clean drinking water in remote and off-grid environments. The integration of compact design, efficient pressure control, and proper maintenance further enhances the feasibility of solar-powered RO systems for sustainable water purification applications.

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2.2 Battery

Energy storage is essential for solar-powered water purification systems to maintain operation during periods of low solar irradiance, such as cloudy weather or nighttime. Choosing the right battery technology impacts efficiency, reliability, portability, and maintenance. Lithium-ion batteries are increasingly favoured over traditional sealed lead-acid (SLA) batteries due to their superior performance.

Lithium-ion batteries have advantages over SLA batteries, such as higher energy density, longer cycle life (over 2000 cycles), lower self-discharge, and better charging efficiency [9]. They are also lighter and more compact, making them ideal for portable systems. In contrast, SLA batteries are heavier, have a shorter cycle life (300–500 cycles), degrade when deeply discharged, require longer charging times, and are less efficient under partial charge, negatively affecting solar-powered applications.

Maintenance requirements are an important factor. SLA batteries require periodic maintenance and are sensitive to temperature fluctuations, which can shorten their lifespan when used outdoors. In contrast, lithium-ion batteries are typically maintenance-free and better tolerate temperature changes, making them ideal for remote off-grid installations.

This project uses 18650 lithium-ion batteries (3.7 V, 4800 mAh) and a Battery Management System (BMS) to ensure safe operation, prevent overcharging and overdischarging, and extend battery life. Integration supports sustainability, efficiency, and portability, providing a stable energy supply for the solar-powered water purification system [10].

2.3 Sensor, Switch, and Energy Control Summary

Automation is crucial for enhancing the reliability and efficiency of solar-powered water purification systems, especially in off-grid settings where manual monitoring is impractical. Previous studies have utilised automation techniques such as microcontroller systems, water-level sensors, and automated valve control to improve stability and minimise user intervention. For instance, Arduino-based systems regulate pump operations, monitor water quality, and optimise energy use according to solar availability. While these improvements enhance performance, they can also increase complexity, cost, and maintenance requirements, making them less suitable for low-cost and portable applications. Fig. 1 depicts the project's overall process.

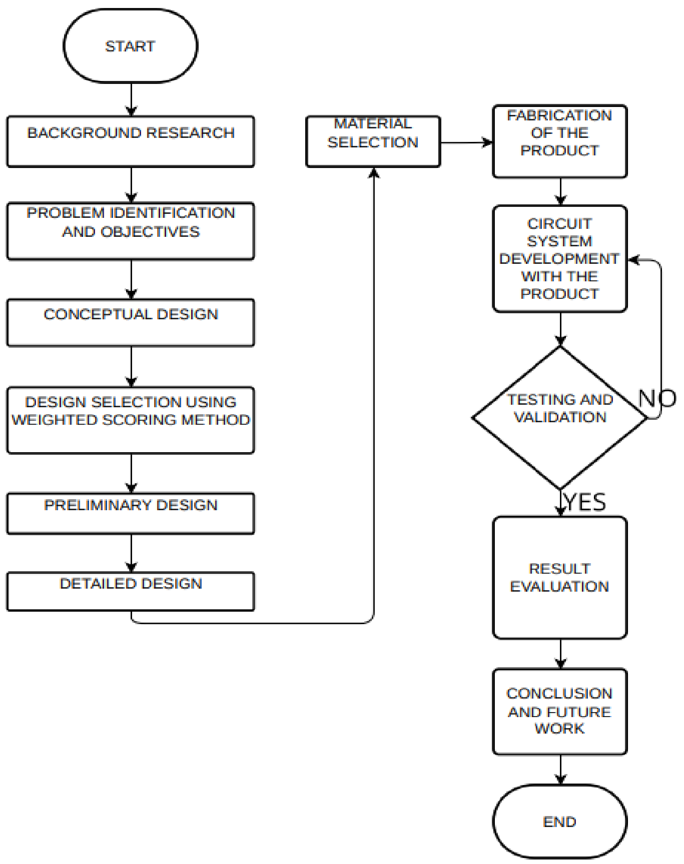


Fig. 1 *Project Development Flowchart*

This project adopts a simplified automation approach using a float switch sensor to monitor water levels and control pump operation, preventing overflow and dry-run conditions that can damage the pump. This method reduces the need for manual supervision while ensuring reliability. Compared to microcontroller-based systems, the float switch offers a cost-effective, low-power solution ideal for rural and off-grid deployment.

A manual switch is included alongside the float switch for maintenance and emergency shutdown, enhancing safety and service flexibility. A 12 V relay manages power flow between the pump and power supply, ensuring efficient energy management and protecting against overloads [11].

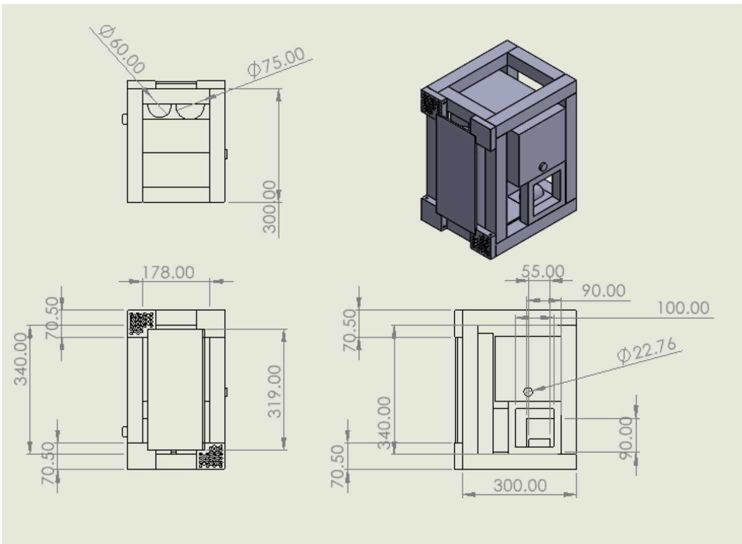
Many studies on automation systems lack simplicity, portability, and affordability for small-scale rural applications. This project addresses these issues by integrating a straightforward automation system that enhances safety, reduces energy use, and improves reliability without adding complexity or cost. This approach makes the proposed solar-powered water purification system better suited to remote and off-grid environments.

3. Methodology

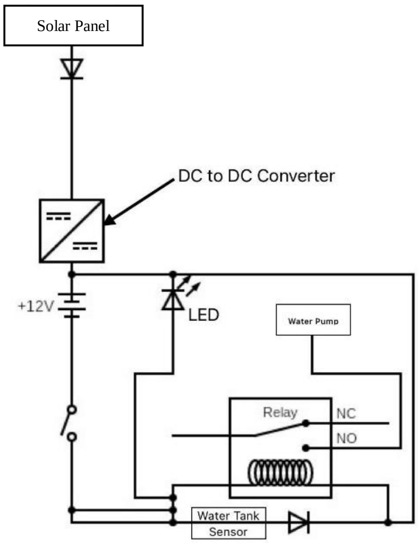
The solar-powered water purification system was developed using a systematic approach comprising five major phases: preparation, design, fabrication, analysis, and verification. The process guaranteed that the finished system was small, cost-effective, and suited for distant or off-grid applications.

A cube-shaped enclosure, as shown in Fig. 2 (a), was designed for the solar-powered water filtration system to ensure portability and ease of integration, featuring a layout that positions a 100W photovoltaic (PV) panel on the front while accommodating electronic components and filters internally, mounted on a rigid and low-weight chassis for enhanced portability.

The simplified float-level circuit schematic diagram is shown in Fig. 2(b). Comprehensive testing and evaluation were conducted under standard operational conditions, focusing on battery performance metrics (including charging time and pump runtime), water output quantification (liters produced per day), and water quality assessments (measuring turbidity, total dissolved solids (TDS), and pH levels before and after treatment), with results meticulously recorded for subsequent analysis.



(a)



(b)

Fig. 2 *(a) CAD Design of the Solar-Powered Water Purification System (b) Float level schematic diagram*

Key components were selected, including a 100W monocrystalline solar panel, a 3.7V, 4800mAh lithium-ion battery with battery management system (BMS), a DC-DC converter, a 12V pump with a flow rate of 800 L/h, a float-level switch, and filtration elements comprising an activated carbon cartridge and reverse osmosis (RO) membrane, as detailed in the accompanying table. The prototype was fabricated by cutting and welding mild steel bars and 3D-printing panels and supports from polylactic acid (PLA), followed by the assembly of electrical components, such as the maximum power point tracking (MPPT) controller and filtration cartridges, within the enclosure. System integration involved the PV panel charging the battery via the controller, which subsequently powered the 12V pump; the pump drew raw water that first passed through the carbon filter and then through the RO membrane, with a solenoid valve controlled by a float switch at the outlet tank to ensure automatic shutoff when water levels reached a certain threshold.

3.1 Cost Estimation

For comparison, commercial small solar RO units often run several hundred dollars; our bill of materials shows that with basic parts and 3D-printed supports, a viable system can be built economically.

Table 1 *Cost estimation of the Solar-Powered Water Purification System*

Material Name	Size/Specification	Quantity	Total Cost (RM)
Solar Panel Set	With a 100W Solar Panel, a 12VDC Water Pump and a Circuit with a Control Box	1	127.00
PLA 3D Printer Filament	1.05kg x 1.75 mm	1	69.00
Float Switch Sensor	-	1	15.00
RO Membrane & Housing	-	1	71.00
Carbon Filter & Housing	-	1	19.00
Water Tank	100 mm × 200 mm × 330 mm	1	16.00
Polyurethane Hose (1/4")	3 meters	1	16.00
Mild Steel Square bar	40 mm x 40 mm x 1200 mm	1	18.00
Mild Steel Square bar	20 mm x 20 mm x 720 mm	1	7.00
Mild Steel Plate	25 mm x 3 mm x 500 mm	1	4.00
Total			362.00

Table 1 shows the total cost of developing a prototype of the solar-powered water purification system. The table only summarizes the total cost of materials and does not include fabrication, testing, or other miscellaneous costs. This low cost illustrates affordability for household use.

4. Results and Discussions

4.1 Testing Methodology

Several functional and performance tests were used to assess the solar-powered water purification system's performance. Among the tests performed to assess performance are the machine subsystem functionality test, the solar charging and discharge test, the water output test, and the water quality test. The preliminary system test is implemented with a complete system installed to assess whether the system is fully operational, including the RO membrane and filtration components. During the test, the control system, including the float level switch, is observed to verify its designed function, with no water leaks in the pumping, delivery, and filtration system and no electrical or electronic issues arising.

4.2 Solar Charging and Discharge Test

The solar panel charging efficiency was tested by measuring the time required to charge the battery pack under bright sunlight. The system utilises three lithium-ion batteries with a combined capacity of 18,500 mAh.

Table 2 *Solar charging and discharge time*

Test Cycle	Charging Time (hrs)	Discharge Time (hrs)
1	4.50	2.00
2	4.54	3.00
3	4 .30	2.00
Average	4.45	2.33

Testing was performed over three cycles, and the results are summarized in Table 2. The test was conducted between 10.00 am to 4.00 pm during normal daylight hours at the same location. The battery is charged by a 100W solar panel connected through a DC-DC converter. For discharge tests, a 12 VDC water pump runs continuously to simulate continuous pumping conditions. The time taken to discharge the battery to its lowest energy stored is recorded. The test results are shown in Table 2. The average charging time is 4.45 hours, and the average time to almost fully deplete the battery is 2.33 hours. The average time to discharge exceeds 2 hours, indicating that the system can achieve the targeted filtered water capacity. However, the time required to fully charge the battery depends on the amount of sunlight.

4.3 Water Output Rate Test

The water output rate test was conducted to determine the actual water production efficiency. With a fully charged battery, the pump was activated, and the time required to collect 1 Liter of purified water was recorded. Across three trials, the average time observed was approximately 2 hours and 13 minutes per Liter, significantly slower than the theoretical calculation which is 1 Liter/hours. This deviation is likely due to pressure losses across the filters, the RO system's energy demand, and the system configuration. One factor contributing to this deviation is the selection of a low-pressure water pump. The pressure drop across the RO filters is significant, reducing the pumped water flow rate and increasing the time required for production. Nonetheless, slow but steady output is suitable for low-volume daily consumption in off-grid areas, especially where reliability is prioritised over speed.

Table 3 *Water output time*

Test Cycle	Production Time (hrs)
1	2.30
2	2.20
3	2.15
Average	2.21

The test results are shown in Table 3. The system operates at 12V with an 800 L/h pump that delivers purified water steadily. During testing, it took about 2.22 hours to produce 1.0 liter of purified water, resulting in an output rate of approximately 0.45 L/h. This rate is modest due to backpressure and flow restrictions from the reverse osmosis (RO) membrane and filters. Ideally, without restrictions, the pump could yield around 13.3 L/h. In practice, our flow rate was 0.4–0.5 L/h, consistent with other low-pressure solar systems. For instance, Tekle Tafere et al. [12] achieved about 0.3 L/h with a hybrid solar still. The estimated specific energy consumption (SEC) of the system is around 0.055 kWh/litre, or 55 kWh/m^3. This is higher than that of large RO plants (2–4 kWh/m^3) [13] but expected for a small prototype, mainly due to the pump's low efficiency at low pressure. Overall, the system produced consistent water, yielding about 3.6 liters over an 8-hour sunny day, sufficient for basic household needs, estimated at about 9 liters per person per day for drinking and cooking.

4.4 Water Quality Testing

Several laboratory tests were conducted to measure the physical and chemical properties of the treated water and evaluate the efficacy of the solar-powered water purification system. These consist of Total Suspended Solids (TSS), Total Dissolved Solids (TDS), and pH determination in the laboratory. Every parameter provides vital information about water quality, indicating whether it is safe for human consumption.

4.5 pH (Potential of Hydrogen)

The pH test was conducted on the sample obtained from the river water and the filtered water from the machine. The test was done using Johnson Universal Indicator Strips (pH range 0-14), which offer a rapid visual assessment of the acidity or alkalinity of the samples. According to the chart, the river water is more acidic, with a pH of approximately 5, while the filtered water has a pH between 6 and 7, suggesting near-neutral conditions. Despite filtered water's more neutral pH, the two samples' physical characteristics differed significantly. The river water appeared to contain more visible solids and colouration, suggesting the presence of suspended particles and dissolved organic matter. In contrast, the RO water sample was clear, indicating low total dissolved solids (TDS) due to filtration. This highlights the importance of not relying on pH alone to assess water quality.

4.6 Water Quality Test

Before treatment, raw water contained elevated levels of contaminants, including Total Suspended Solids (TSS) at approximately 30 mg/L, Total Dissolved Solids (TDS) around 700 mg/L, and a pH of about 7.0. After purification, all parameters improved significantly. The TSS dropped to nearly 0 mg/L, and the TDS decreased well below drinking water standards, falling from approximately 700 mg/L to around 100 mg/L, which is below the WHO guideline of 500 mg/L [14]. The final pH remained neutral at approximately 7.2. Notably, the reverse osmosis (RO) membrane effectively removed most dissolved salts and organic materials. These results align with existing literature on the combination of reverse osmosis and carbon filtration, with both RO and ultraviolet (UV) treated water typically meeting WHO guidelines. For instance, Dirisu et al. found that RO-treated borehole water had TDS below 17 mg/L, with all parameters within safe limits [14]. Our findings similarly suggest that the treated water is of safe potable quality. Therefore, the prototype consistently produces safe water with neutral pH and low solid content.

Table 4: *Total Suspended Solids (TSS)*

Sample	Volume (mL)	River Water (RW) (g)			Filtered Water (FW) (g)			RW	FW
		Filter Weight	Filter + Solids	Weight of Solids	Filter Weight	Filter + Solids	Weight of Solids	TSS (mg/L)	TSS (mg/L)
1	50	0.1532	0.1545	0.0013	0.1521	0.1522	0.0001	26	2
2	50	0.1515	0.1528	0.0013	0.1473	0.1474	0.0001	26	2
3	100	0.1486	0.1494	0.0008	0.1534	0.1535	0.0001	8	1
4	100	0.1500	0.1512	0.0012	0.1466	0.1468	0.0002	12	2

Table 5: *Total Dissolved Solids (TDS)*

Sample	Volume (mL)	River Water (RW) (g)			Filtered Water (FW) (g)			RW	FW
		Dish Weight	Dish + Sample after drying	Weight of Solids	Dish Weight	Dish + Sample after drying	Weight of Solids	TSS (mg/L)	TSS (mg/L)
1	100	83.76	83.84	0.08	82.55	82.56	0.01	800	100
2	100	86.54	86.70	0.16	62.62	62.63	0.01	1600	100
3	100	78.82	78.94	0.12	84.44	84.46	0.02	1200	200

Water quality tests are summarised in Table 4 and Table 5. If the comparison was made between the developed machine and the recent technologies. Our pump operates at approximately 4–5 bar, typical for small brackish reverse osmosis (RO) systems, while seawater RO plants function at 50–60 bar [13]. Our energy consumption is about 55 kWh/m^3, higher than large RO plants (2–4 kWh/m^3) [13] and UV disinfection systems (less than 0.1 kWh/m^3) [15], but like other small photovoltaic (PV)-RO prototypes, like a solar-RO pilot using around 40 kWh/m^3. Maintenance primarily involves cleaning and replacing membranes every few months and changing carbon filters annually. This aligns with common practices, such as yearly UV lamp servicing and 6–12-month [15] air conditioning filter replacements. While our system lacks remote sensors, it features an automatic float switch that prevents overflow, making it easier to use. In contrast, advanced IoT/SCADA desalination systems include networked sensors for leak detection and pump control, but at a higher cost [16]. Overall, our results show that a simple solar-RO system with UV and carbon filtration can meet safety targets, although efficiency trade-offs and manual operation remain challenges.

5. Conclusion

A proof-of-concept solar-powered water purifier was successfully designed and tested. The system achieved its primary objectives: it operated entirely on photovoltaic (PV) energy and produced potable water devoid of toxic residues. The key findings of the study include: (1) The battery-supported pump system demonstrated the capability to operate for several hours following a complete solar charge, thereby validating the energy storage design; (2) The water quality produced met established potable standards, indicating the effectiveness of the integrated filtration stages[13]; (3) The total material cost was approximately RM362, highlighting the economic viability of the system. These findings align with existing literature that characterizes solar water purification as “a promising and sustainable solution” to the challenges of water scarcity [12]. Although the project yielded positive results, it also identified several areas for enhancement. For instance, incorporating a small automatic agitator could improve mixing efficiency, and an advanced maximum power point tracking (MPPT) controller could enhance overall energy efficiency. Future research may explore the integration of remote monitoring (IoT connectivity) and mechanical stirring to further optimize system performance. In conclusion, this study affirms that a straightforward, solar-powered, manually operated water purifier can effectively treat household water, thereby reinforcing the case for decentralized, renewable-driven water treatment solutions in marginalized communities [12], [13].

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Sin Kai Sheng, Arthur Ang Jun Rong, Ahmad Faiz Bin Mat Zian, Muhammad Sufi Bin Roslan, Nadira Binti Johari Halim Shah;* ***data collection:*** *Sin Kai Sheng, LidhyaShree Devi, Arthur Ang Jun Rong;* ***analysis and interpretation of results:*** *Sin Kai Sheng, Arthur Ang Jun Rong, LidhyaShree Devi, Ahmad Faiz Bin Mat Zian, Muhammad Sufi Bin Roslan, Nadira Binti Johari Halim Shah;* ***draft manuscript preparation:*** *LidhyaShree Devi, Arthur Ang Jun Rong, Sin Kai Sheng, Ahmad Faiz Bin Mat Zian. All authors reviewed the results and approved the final version of the manuscript.*

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